

Optical Multicolor Observations of the SS 433=V 1343 Aql Microquasar

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Abstract

We report BVR photometry of the V1343 Aql= SS 433 microquasar at different phases of the 13-day orbital cycle for the 1986–1990 observing seasons. The data include five complete cycles of the 163^d precession period of the system. We obtain mean light curves and color–color diagrams with the orbital period for all intervals of precession phases. The optical component of the close binary system (CBS) fills its critical Roche lobe and loses mass on the thermal relaxation time scale. Gaseous flow show up actively in the system and activity manifestations differ substantially at different precession phases.

The collimated relativistic jets perpendicular to the plane of the disk appear to be associated with supercritical accretion onto the compact relativistic object in the massive CBS, which shows up in the shapes of the light curves at different orbital and precession phases. An analysis of color indices confirmed the earlier discovered peculiarities of the system [1]:

(1) A "disk corona" around the compact object.

(2) Phase shifts between orbital light curves and different heights of light maxima for different passbands and at all phases of the 163^d precession period.

Introduction

The unique astrophysical object SS 433 (V1343 Aql), $\alpha = 19^h 11^m 49^s.56$, $\delta + 04^\circ 58' 57''$.6 (J2000), has been for many years attracting attention of observing astronomers as well as theoretical physicists all over the world. The evolutionary status of the close binary system SS 433 is the X-ray stage of massive close binary systems (MCBS). The active state of these stars, which are at the X-ray stage of their evolution, is explained by a spectrum of changes in the process of accretion of material on the

CBS compact object. However, SS 433 is strongly distinguished among other X-ray sources by that in the X-ray range radiate X-ray jets, not the accretion disk [2].

The high rate of accretion on the compact object ($\sim 10^{-4} M_{\odot}/\text{year}$) produces these jets aligned with the accretion disk axis. The velocity of gas in the jets is $\sim 80,000 \text{ km/c} = 0.26c$. The orbital period of the system is 13.082^d , and the precession period of the disk and jets is 162.5^d [3], [4].

The main minimum of the orbital light curve corresponds to the eclipse of the accretion disk by the normal star. In this CBS the optical star is at a later evolutionary stage. It overfills its critical Roche lobe and outflows onto the relativistic object on the thermal relaxation timescale at a rate of $\sim 10^{-4} M_{\odot}/\text{year}$. This results in supercritical accretion onto the relativistic object [5], because the appearance of collimated relativistic outflows of material from the central parts of the thick accretion disk is a novel and unexpected feature of the supercritical accretion mode.

Simultaneous measurements of brightness in several spectral bands will yield unbiased information for undistorted colors of the object SS 433 and for updating existing models of it.

Observations

Systematic photoelectric *BVR* observations (*W* band observations are also available) were carried out by the author in 1986–1990. They are listed in Table 1, which can be found at (<http://lnfm1.sai.msu.ru/~sazonov/V1343 Aql=SS 433>).

In these observations the mean errors in the *BVR* spectral bands were from $0^m.010$ to $0^m.035$.

In total we have obtained 1129 individual measurements in 295 nights during five years of observations. The observations were carried out with single-channel *WBVR* photometers on the following instruments: 600-mm reflector of the Crimean Laboratory of the Sternberg Astronomical Institute (Ukraine, altitude above sea level 550 m) with a $27''$ diaphragm in the *WBVR* instrumental photometric system; Zeiss–600 reflector on Mt. Maidanak (Uzbekistan, altitude above sea level 2600 m); 480-mm reflector of the Trans-Ili Alatau Observatory (Kazakhstan, altitude above sea level

2760 m).

We have used as a radiation detector a FEU-79 photomultiplier tube (S-20 multi-alkali photocathode). The broadband *WBVR* system has been used owing to its better determinacy. The system was described by [6].

Reduction to the standard system

In electrophotometric observations of great importance is proper matching of instrumental corrections to the standard Johnson photometric system. In joint observations with T.R. Irsmambetova at the Mt.Maidanak Observatory in 1987–1989 the author used the reduction coefficients of the instrumental system in the work on the Zeiss-600 telescope (single-channel *WBVR* electrophotometer with automatic control system; as a radiation detector a FEU-79 photomultiplier tube was used).

The relative spectral sensitivity of the system was rather stable. It was checked twice in the observational season (spring–summer and summer–autumn).

The coefficients of reduction to the standard photometric system were obtained from repeated measurements of standard stars in the areas SA 107, 108, 111–113 [7].

We have the following quantities:

$$B - V = 1.071(b - v) - 0^m.068$$

$$(\pm 0.021)(\pm 0.018)$$

$$V - R = 0.803(v - r) + 0^m.173$$

$$(\pm 0.033)(\pm 0.014)$$

instrumental *bvr* stellar magnitudes; *BVR* stellar magnitudes in the Johnson photometric system.

To calculate corrections to the determined stellar magnitudes from the known instrumental color indices we use the following expressions:

$$B - b = 0.094(b - v) - 0^m.099$$

$$V - v = 0.014(b - v) - 0^m.015$$

$$R - r = 0.234(v - r) - 0^m.208.$$

In subsequent observations of 1991–1998 (including those at other observatories) we derived the coefficients of reduction to the standard Johnson photometric system from measurements of standard stars in the areas of h and χ Per (NGC 869, the author measured 12 standard stars) and NGC 884 (13 standard stars).

It should be noted that, owing to the extremely faint brightness of the object SS 433, short integration time of the useful signal, $60^s - 90^s$, and small aperture of the telescopes used (Zeiss-600), the W -band data were obtained only at the instants of the maximum light of the system (T3) with a temporal resolution of 5–6 min on a time interval of 3–4 h (more seldom ~ 5 h).

On medium-aperture telescopes (1200 mm; e.g., AZT-11 of the Crimean Astrophysical Observatory) we had rms errors of the measurements estimated from pulse statistics with regard to background at the periods of maximum light $0^m.045$, $0^m.035$, $0^m.020$, $0^m.015$, $0^m.015$ in the $UBVRI$ bands, respectively.

On small instruments (with an aperture of 480–600 mm) in the BVR bands we had rms errors estimated from pulse statistics with regard to the background in the periods of maximum brightness $0^m.040$, $0^m.020$, $0^m.008$ in the B , V , R bands. The mean errors of the estimated brightness can reach $0^m.08$ in the W band, $0^m.04$ in the B band, and do not exceed $0^m.03$ in the V , R bands.

Ephemeris

In this work we have used photometric elements of the middle of eclipses (phases ϕ) and maxima of the out-of-eclipse brightness (phases ψ) taken from [8], [1], respectively:

$$\text{Min I Hel} = 2444332^d.98 + 13^d.086 \cdot E \text{ (phasa } \phi\text{)}$$

(phase $\phi = 0$ corresponds to the instant of the occultation of the accretion disk by the “normal” star) and

$$\text{Max} = \text{T3} = 2443666^d.29 + 163^d.34 \cdot E \text{ (phasa } \psi\text{)}$$

(where T3 is the instant of the maximum separation of the moving emission lines).

It is accepted that at this instant $\psi = 0$.

All photometry was done with respect to the comparison star C1 = Kemp1 [12] and reference star B as in [1]:

(C1=GSC 0471-01564 $19^h 11^m 47^s.66 + 5^\circ 00' 35''$.0 (J2000));

(B=GSC 0471-00142 $19^h 11^m 47^s.04 + 4^\circ 59' 38''$.1 (J2000)),

The star C1 was linked to standards from the list of [9]:

$U=14^m.22$; $W=14^m.14$; $B=12^m.93$; $V=11^m.46$; $R=10^m.09$.

For the reference star B we took magnitudes:

$B=14^m.57$; $V=13^m.46$; $R=12^m.52$.

Interpretation of the observations

All observational data reported in this paper as well as their interpretation were compared with similar works of other authors for the last 30 years:

[1], [4], [16], [17], [18], [19], [20], [21], [22], [23], [24], [26], [27].

Optical light curves of the close binary system (CBS) V1343 Aql = SS 433 obtained in B, V and R bands for the period 1986-1990 are qualitatively similar (Fig. 1a, 1b and 1c).

The average depths of the primary minimum (when the accretion disk around the tight companion is occulted by the "normal" star) for this period is $0^m.65 - 0^m.75$, $0^m.50 - 0^m.60$ and $0^m.35 - 0^m.45$ mag in B , V and R -filters, respectively.

The light curves evolve during the precession cycle of the system which may be attributed to the gas streams activity in the CBS and their interaction with the "floating" accretion disk which spatial orientation drive the direction of the relativistic jets.

Phase shifts of the orbital light curves and variation of the maxima heights confirm the presence of asymmetry of the brightness distribution in the accretion disk. They also support the fact that the backside of the disk (with respect to the orbital motion) is more luminous which was first noticed in [1].

The variations of color indices with the orbital and precession periods are well confirmed for Min I and Min II by the above mentioned observation seasons (see, for

example, the 1988 data in Fig. 2a, 2b, 2c and Fig. 3a, 3b, 3c).

Analyzing the photometric data, we should pay special attention to comparative and qualitative analysis with early works of the author.

The small amplitude of chanzing of color index $B - V$ is clearly seen on the diagrams of color indexes.

Evidently this is one of the consequences of relatively small difference in the $B - V$ color of thermal continuum, radiated by the bright optical star and different parts of accretion disk in the system [1], because at temperature higher an 20000 K the color $B - V$ of optical radiation practically does not depend on the temperature.

We should note that the character of periodic brightness variations of SS 433 in these observing seasons is in qualitative agreement with the date from othei authors for the period 1978–1990.

This allows us to conclude about some stability of regular brightness variations with periods 163^d (precession period, amplitude $\Delta V = 0^m.75 \div 0^m.85$), $13^d.086$ (orbital period, amplitude $\Delta V = 0^m.80 \div 0^m.90$).

In the observing period 1986–1990 a the series 5–7 flares were observed each observing season (the object was especially active in 1988) with amplitude frow $\sim 0^m.30$ to $\sim 0^m.50$ in the V band.

The flares of optical radiation of SS 433 in these observing seasons are distributed nearly evenly on all the phases of precession period.

Undoubtedly, the amplitude and shape of the orbital light curve of the system is functionally dependent on the precessional phase of the appearance of the relativistic jets in space. This is well visible from the comparison of orbital light curves for different observational seasons (see, e.g., 1986 and 1988) at the same precessional phases.

In these observations rms errors estimated from pulse statistics with regard to the background in periods of maximum brightness were $0^m.040$, $0^m.020$, $0^m.008$ in the B , V , R bands, respectively. Mean errors of brightness estimates may reach $0^m.08$.

In the regular precessional variability the out-of-eclipse CBS brightness also changes with the precessional phase, and at instant T3, $\psi = 0.0$ (maximum separation of the relativistic emission lines) the brightness is maximum ,whereas near $\psi = 0.5$ the

brightness is minimum. This is visible rather clearly in all graphs of this observational interval.

These, relatively regular variations are superimposed by unpredictable bursts of brightness, which are caused by the active state of the object (these properties of the object persisted during all the years of the author's observations). The brightness increase during these bursts is of the order of $\Delta V_{max} = 1^m.2$.

The largest fluctuations of brightness take place at instant T3 ($\psi = 0.00$), which corresponds to the maximum opening of the disk toward the observer. Near the phase $\psi = 0.50$, when the disk turns its other pole to the observer, the scatter of the observed points becomes minimum; this is well visible from the lower envelope of the light curve. This is especially notable in the seasons of 1987 and 1989.

In these seasons the accuracy of the photometric maxima (T3) was not very high because of substantial distortions of the orbital light curves due to the activity, which may last up to 90 days and longer. The upper level of the light curve is more rarefied, and it is formed by separate flares.

The system's flare activity

On the basis of long-term photometric observations and of their analysis, many authors have established that the object SS 433 spends in the active state more than 20% of the time. In the optical range its flare activity manifests itself differently. Sometimes series of flares are observed, and sometimes isolated flares appear with a V band amplitude of $\sim 0^m.8$ and with varying duration.

A series of flares can last up to 40% of the precessional period. It results in an appreciable chaos in the light curve geometry. Similar phenomena were observed, e.g., in 1979, 1980, 1982, and 1986 (literary data) as well in the observations of 1988 (this work).

In these observational seasons the optical flares of SS 433 are distributed almost uniformly over all phases of the precessional period, as it is visible from the entire observational database reported here.

Note prolonged flares recorded in these observational seasons:

The system's flare activity in 1986 was detected during:
JD 2446619, JD 2446625, JD 2446652, JD 2446715.

The system's flare activity in 1987 was detected during:
JD 2446995, JD 2447016, JD 2447062, JD 2447064, JD 2447082,
JD 2447094, JD 2447096.

The system's flare activity in 1988 was detected during:
JD 2447318, JD 2447423, JD 2447327, JD 2447345, JD 2447360.

The flare at observing date JD 2447434 has the following parameters: $0^m.758$ in *B*-band, $0^m.512$ in *V*-band, $0^m.252$ in *R*-band. The $\varphi = 0.992$, $\psi = 0.068$ in this case.

The system's flare activity in 1989 was detected during:
JD 2447712, JD 2447721, JD 2447734, JD 2447747, JD 2447748,
JD 2447798, JD 2447800.

The system's flare activity in 1990 was detected during:
JD 2448105, JD 2448190–JD 2448191.

The star's nutation light curve

We also analyze the nutational light curve of the object based on optical observations made in 1980–1990 (see paper [1]): we first subtracted the precessional and orbital variations and phased the residual with the 6.28-day nutational period (Fig. 4a, 4b, 4c). The nutational light curve qualitatively resembles a similar light curve from [22]. We adopted the ephemeris for the maxima of the nutational variations from [30].

The nutation phenomenon manifests itself as wobble of the relativistic jets in the system.

Nutation is the third reliably established period in the optical light variations of SS 433. It is accepted that, irrespective of the CBS precessional orientation in space, total eclipses of the accretion disk by the optical star are never observed in SS 433.

All these regularities testify that in the CBS SS 433 there are partial eclipses of the precessing accretion disk by the “normal” star.

From the analysis of the five-year photometric database we obtain that the nutational period remains stable within the errors of the observations and

mathematical processing.

In the interpretation of the observational data of the seasons of 1986–1990 (together with unpublished author's data of 1991–1994 and 1996–1998) attention is drawn to some data obtained near precessional phases $\psi = 0.00 \pm 0.16$ (T3, the instant of the maximum separation of the relativistic emission lines), which have found no satisfactory explanation in the framework of generally accepted other authors' scenarios of the behaviour of the CBS SS 433 = V1343 Aql. In this paper the author attempted to explain the above-mentioned observational features of the system.

At precessional phases $\psi = 0.02 – 0.16$ (and different orbital phases ϕ) there are observed points at which the brightness has an increased amplitude (but they are not flares, because the points relax rather quickly to the mean brightness) as compared to neighboring points within a relatively short time interval and in brightness.

As a rule, we chose good photometric nights. We selected statistical photometric data in three (more seldom in four) spectral bands to refine the already existing correlations.

Special points on the light curves

Some researchers attribute these features to the nonstationary nature of the activity of SS 433 and to the strong variability of the mass-loss rate in relativistic jets. However, inflection points are by no means the only singularities to be found on radial-velocity curves. Other possible singular points include, e.g., points of self-intersection of gas jets in the system [25].

Sazonov and Shakura [25] already pointed out the above feature of particle trajectories in the gas flow in a close binary system - i.e., their tendency to intersect (even in the celestial-mechanics approximation). The intersection of ballistic trajectories of flow particles may prove to be one of the factors of the formation of irregularities in the gaseous jet. The formation of irregularities may result in the scintillation of the "hotspot" that develops where the jet meets the disklike envelope of the relativistic object of the close binary system or where it intersects with the neighboring trajectories of the jet flow. Possible cases include the the collimated

jet trajectory portions located near time T3 (or, rather, at phases $\varphi=0.03-0.15$).

The authors of papers [32] and [33] and review [34] point out various instabilities of the gas flow in the vicinity of the compact object in the CBS and indicate that the gas-flow instability shows up, among other things, as quasi-periodic oscillations of the mass accretion rate M and the rate of change J of the angular momentum of the matter located near the secondary component of the CBS. The above authors used the computed density, velocity, and temperature fields to calculate the emission profiles of the H??? line, and found the wings of these lines to form near the accretor and their broadening to be determined by the high velocities of the gas flow in the accreting matter and disk. The gas velocities near the accretor were found to exceed the average gas velocity in the system by a factor of more than 10 [33]. This result agrees well with the interpretation of our optical observations.

Furthermore, we also established in our earlier papers that gas in the jet is concentrated in individual clouds [35], [36], [37], in line with the above scenario that explains the observed data points with a somewhat excessive amplitude at precession phases $\psi=0.02-0.16$ (and various orbital phases φ) of SS 433.

Rapid variations of the object

We also performed observations on time scales corresponding to rapid variability, ranging from 90 to 180 s per single exposure. We studied the object over time intervals ranging from 1 to 2.5 hours. The authors of [39] concluded, based on the results of x-ray, optical, and radio observations made with a temporal resolution of 16 s, that individual clouds show up at all wavelengths.

The existence of fast variability in the brightness of the object SS 433 on timescales from several minutes to 20–30 min was established and confirmed in [13], [14], [15]. At the present stage of the study of this object we need high - precision photometric data for updating the existing model of the fast variability and for revealing still unknown mechanisms of its origin.

The observed brightness difference in all spectral bands within the same observational night can be explained physically by fast variability with a timescale

of 10–30 min and amplitude from $0^m.1$ to $0^m.3$ [22], [14], [10].

Parallel photometric and spectral observations of the research team of the Special Astrophysical Observatory [13] have shown that the fast photometric and spectral variability on timescales ~ 10 –30 min is observed in the quiescent state of the system at any phase of the orbital and precessional cycles.

According to the observations in these seasons the main minimum in the B band is deeper than in the other bands, especially at precessional phases $\psi = 0.3, 0.4, 0.5, 0.6$, and 0.7 .

The observations of the season in the mode of the fast variability on timescales from 2 to 3–4 min (the exposure in the BVR or $WBVR$ bands) have confirmed that the dependences of $(B - V)$ on B and $(V - R)$ on V are fulfilled unambiguously: the $(B - V)$ and $(V - R)$ color indices decrease with increasing B and V brightness, respectfully.

The authors of [13] have drawn a conclusion about the causes of fast variability as a result of the passage of the relativistic jets through the circumbinary envelope. At short timescales the fast variability is explained by the discrete character of the jet, which consists of separate ionized gas clouds.

Rapid variability was observed in all photometric bands (variations were found in the BVR data obtained by the author of this paper and in the $UBVRI$ data obtained in [1]). The authors of [1] found that orbital light variations exhibit phase shifts and the heights of the maxima (amplitudes) differ for different passbands and different phases of the 163 - day period.

The amplitude of physical intranight variability of SS 433 may amount to about $0^m.25$ mag or more (see plots for the 1988 season).

The object shows persistent light fluctuations in the R and I bands ([1] and this paper) on time scales of 60 - 90 s. Recent coordinated optical and x - ray observations found such fluctuations in the optical R band on time scales of about 10 s as a result of relatively [40].

The outbursts that occur rather frequently in the system studied produce considerable distortions in the orbital light curves observed during every season. The

1988 season is especially remarkable in this regard.

According to published data, both relativistic hydrogen lines and stationary lines exhibit rapid variations. Relativistic hydrogen lines have a complex multicomponent structure, which varies from night to night. The objects shows variations in the *R* band (see [1] for similar observations in the *R* and *I* bands). The variations involved brightness increases amounting to 0.45^m and 0.35^m in the *R* and *I* bands, respectively, over a 10 - minute long observation (during the same night).

Such variations were recorded several times in *UBVRI* - (1980 - 1986) and *WBVR* - band (1986 - 1990) observations: JD 2445249, JD 2446302, JD 2446995, JD 2447082, JD 2447096, JD 2448053. According to the classification proposed in [22], the "blue" component of emission was present in this case with a color index of $V - R = 1.9$, whereas the "red" emission component was absent.

Conclusions

Our interpretation of the data set obtained during the entire 1986 - 1990 observing period leads us to the following important conclusions:

1. One of the new results of this work is that we obtained simultaneous and homogeneous multicolor observations of the object in the *WBVR* photometric bands. We obtained the orbital light curves of SS 433 at the precession phases of $\psi = 0.0 - 0.1$, $\psi = 0.1 - 0.2$, $\psi = 0.2 - 0.3$, $\psi = 0.3 - 0.4$, and $\psi = 0.4 - 0.5$, thereby extending substantially our cycle of works that we began earlier [1], [25].

2. The manifestations of the activity of the system differ rather significantly at different phases of the 163 - day precession period.

3. During all the observing years the light curve exhibited persistent Min I and Min II, which have the standard depths typical for the precession phase considered in all four - to - five photometric bands observed: the minima do not go below $16^m.779$, $15^m.250$, and $12^m.332$ in the *B*, *R*, and *R* passbands, respectively (in my other papers I report observations made in the *U* and *W* bands using intermediate telescopes [1], [25], [38]).

4. At these times the primary eclipses Min I and Min II appear as rather sharp and deep dips seen against somewhat excessive brightness. The light curve is somewhat

asymmetric - by about 0.006 periods - with respect to the theoretical Min I at time T3. In the quiescent state the orbital light curve covers a single wave per period at this phase.

5. The average magnitude of the system is somewhat brighter than its usual level, by $0.3^m - 0.45^m$.

6. The observed phase shift of the *BVR* light curves (and also in the *U* and *I* - band light curves obtained in 1996) whose magnitudes and signs differ at different precession phases: the eclipse in long - wavelength bands occurs later than in short - wavelength bands ($\psi=0.10 - 0.12$), i.e., first the cooler (dark) regions of the accretion disk are eclipsed, and only then hotter and brighter regions; however, the situation is reversed at the $\psi=0.40 - 0.45$ phase:

6.1. We thus have well - defined phase shifts in the light curves in all the photometric bands observed (*UBVRI*), which are unambiguously related to wavelength.

6.2. Moreover, the maxima (Min I, Min II) are clearly asymmetric at precession phases $\psi=0.10$ and $\psi=0.60$, and this asymmetry is especially apparent in the *B* and *V* bands. It also follows from the asymmetry of the light maxima that at the precession phase of $\psi=0.10$ (and, less conspicuously, but clearly enough, at the phase of $\psi=0.60$) the brightness of the leading part (with respect to orbital motion) of the accretion disk is lower than that of the trailing part.

6.3. Both these features (6.1-6.2) conclusively indicate that the accretion disk of the primary component of the CBS is irregular and asymmetric, and, more generally, that so is the structure of the accretion formation of the entire SS 433=V1343 Aql system.

7. The (W-B), (B-V), (V-R), and (R-I) color indices are functionally dependent on *W*, *B*, *V*, and *R*-band magnitudes. These linear relations strictly obey the pattern: color index decreases with increasing brightness.

8. The source of rapid variations in SS 433=V1343 Aql does not disappear in the system's activity stage and is not eclipsed.

9. The brightness amplitude increases towards shorter wavelengths for all Kinds

of variations of the binary (orbital, precession, nutation variations, rapid variations within a night of observations).

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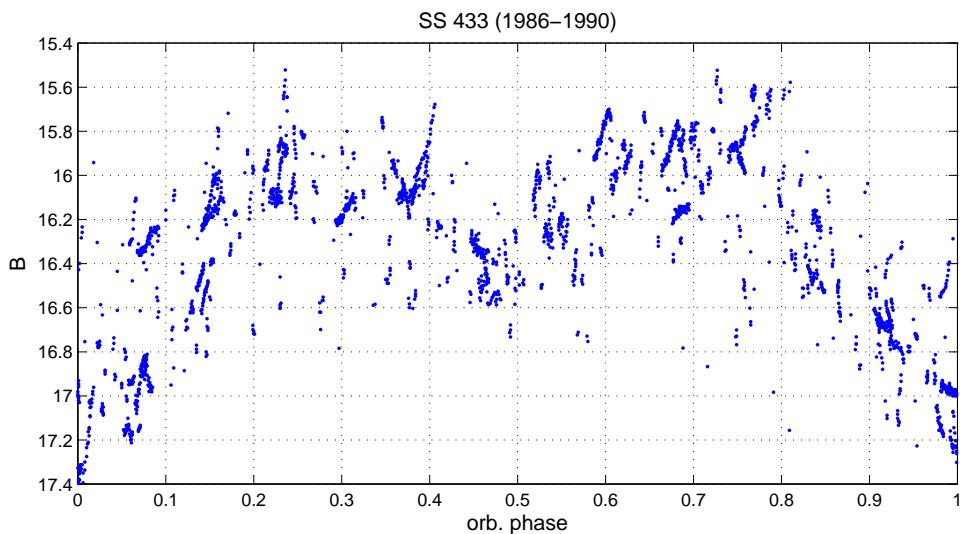


Рис. 1: The 1986-1990 B-band light curve folded with the period $P = 13^d, 086$

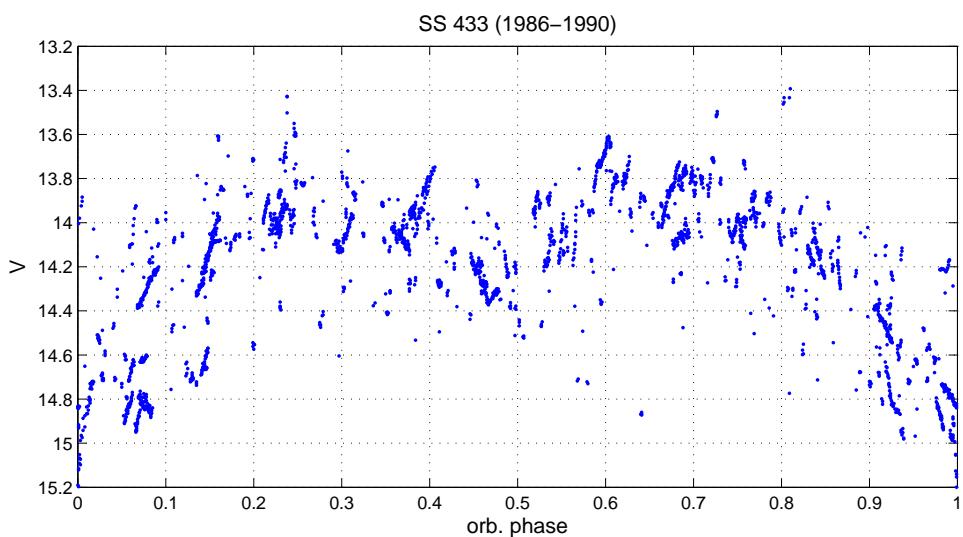


Рис. 2: The 1986-1990 V-band light curve folded with the period $P = 13^d, 086$

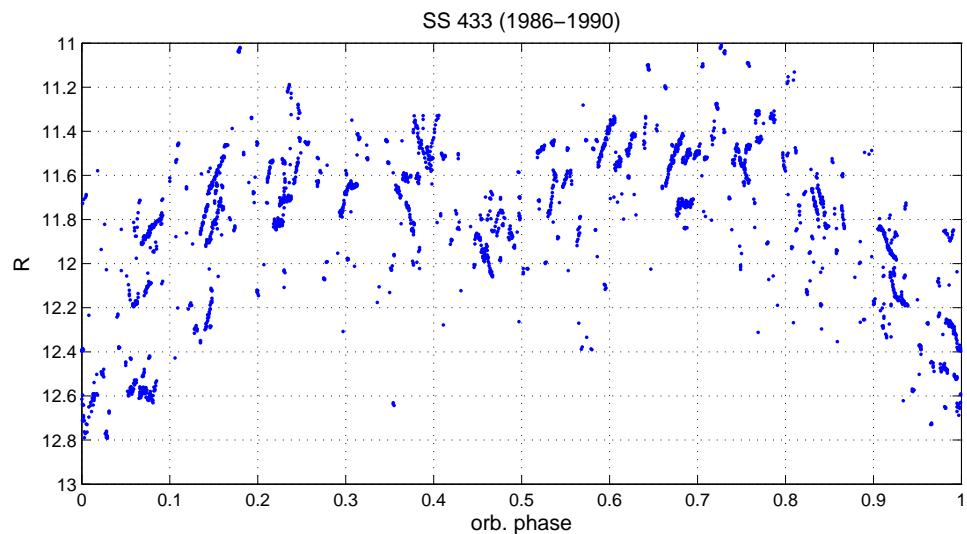


Рис. 3: The 1986-1990 R-band light curve folded with the period $P = 13^d, 086$

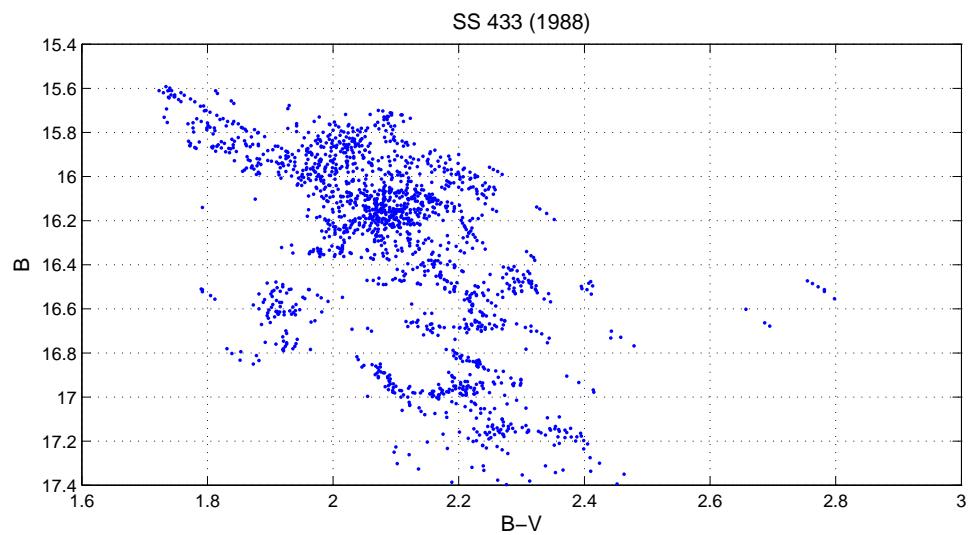


Рис. 4: The 1986-1990 B–V color of SS 433 as a function of B-mag

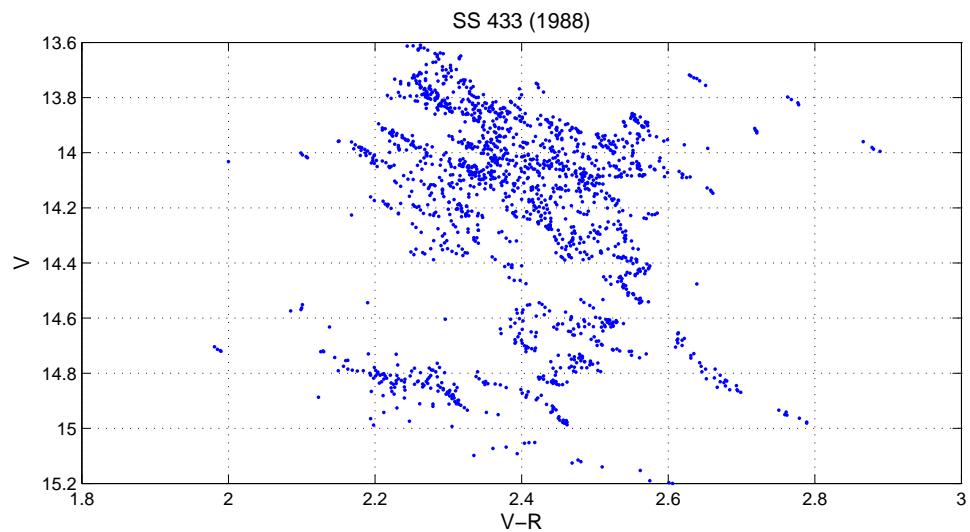


Рис. 5: The 1986-1990 V–R color of SS 433 as a function of V-mag

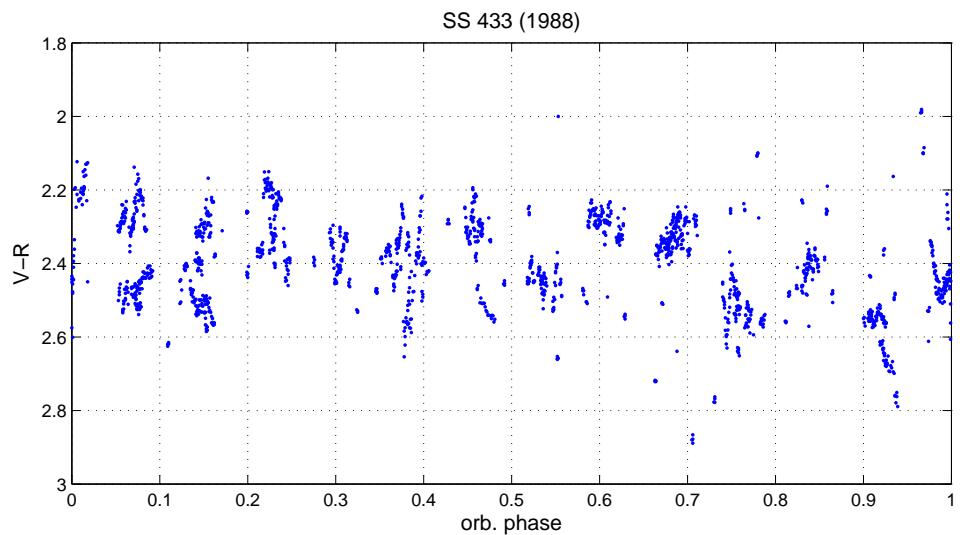


Рис. 6: SS 433 (1988): V-R as a function of the orbital phase

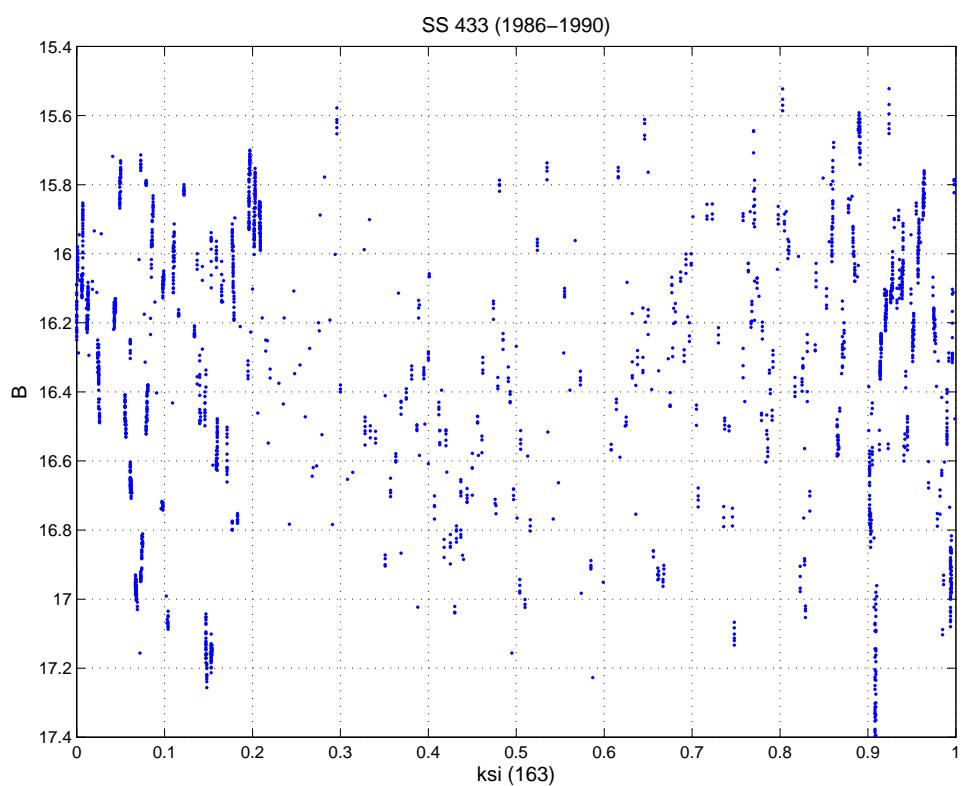


Рис. 7: The 1986-1990 B-band light curve folded with the precession phase

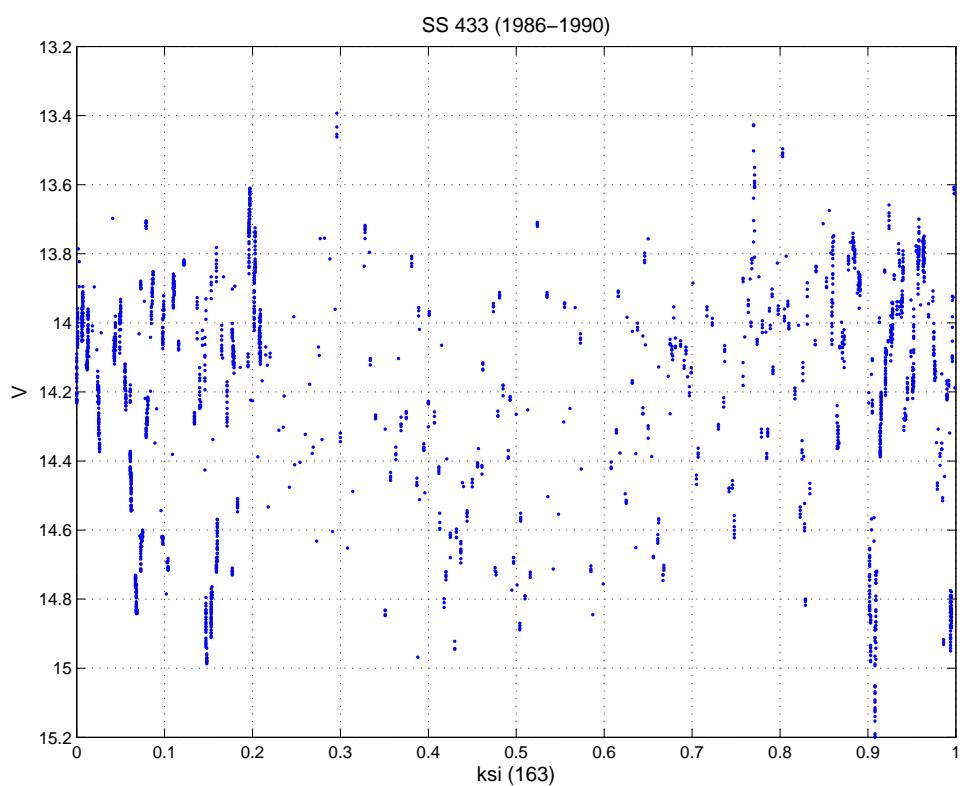


Рис. 8: The 1986-1990 V-band light curve folded with the precession phase

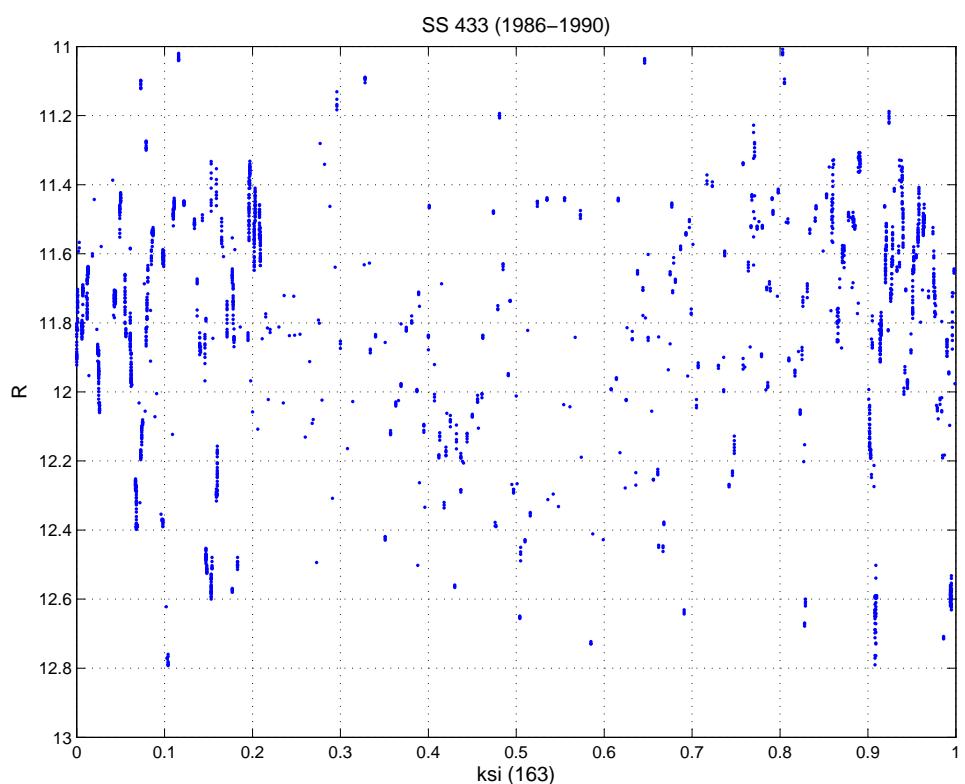


Рис. 9: The 1986-1990 R-band light curve folded with the precession phase

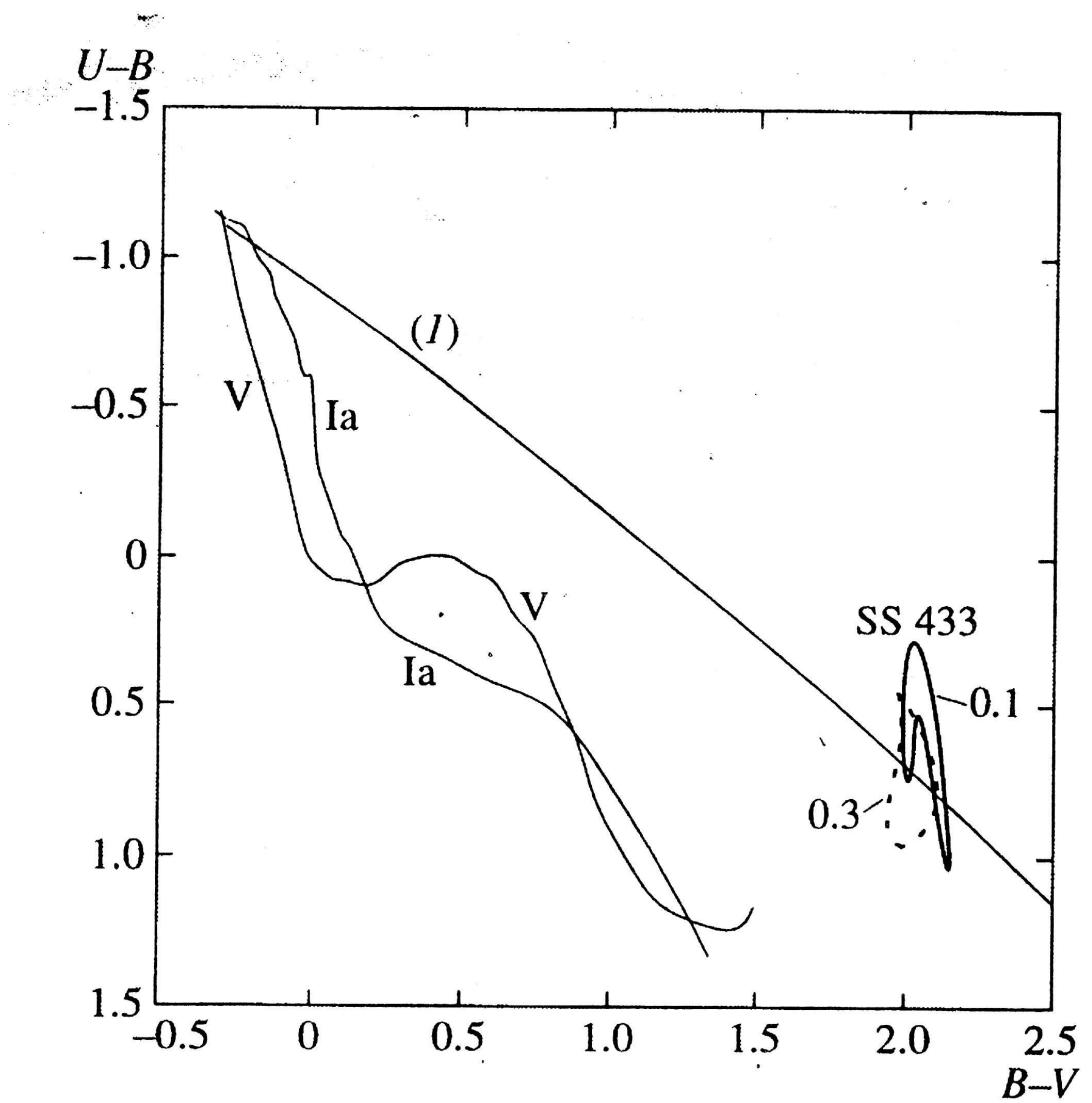


Рис. 10: Smoothed orbital tracks of SS 433 on two-color diagram $U-B$, $B-V$. Mean precession phases are indicated by the numbers. Normal color curves for dwarfs and supergiants and reddening line for not stars are shown by the solid lines.